ANALOG TO DIGITAL CONVERSION TECHNIQUES IN IMPLANTABLE DEVICES

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ABSTRACT

This paper describes an Analog to Digital Converter(ADC) system used in an implantable cardiac pacemaker. The system consists of two types of converters. The first converter uses a single slope technique to measure battery and lead voltages, as well as blood temperature. The second converter is a high speed voltage to pulse width converter which is used to digitize the EKG waveforms on the heart leads.

The digital data from these converters are stored and processed in the pacemaker's microprocessor and memory circuitry.

INTRODUCTION

The conversion of analog signals into digital format has become an extremely important concept in implantable cardiac pacemakers. The analog functions which have been digitized are as follows:

Battery Voltage
Current Drain
Blood Temperature
Cell Impedance
Lead Impedance
R-wave Amplitude
Pattern Recognition
Capture Verification

The specifications for the ADC system in implantable devices have a number of unique and complex requirements. The system is powered by a lithium battery with an operating voltage of 2.78 V. The ADC must draw little current and it must operate over a 2 - 3 V voltage range.

This paper looks at the design and development of an ADC system, which is used in an implantable microprocessor-controlled pacemaker. This system consists of two different types of A/D converters. The first is a single slope ADC, which is used to measure the battery characteristics, lead impedances and blood temperature. The second is a high speed pulse width converter, which is used to digitize the EKG waveform. Each of these have their own characteristics and are discussed below.

SINGLE SLOPE ADC

A block diagram of the single slope converter is shown in Figure 1. The main parts of this system are a storage capacitor, a discharge current source, a comparator & precision voltage reference, and a crystal controlled clock & counter.

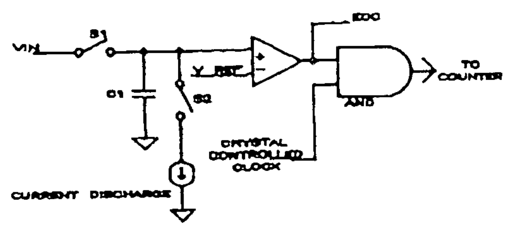

FIGURE 1
SINGLE SLOPE A/D

The operation for reading a voltage is as follows: S_1 is closed and V_{in} is applied to C. After a sufficient charge time S_1 is opened, the counter reset and S_2 is closed. The capacitor is discharged at a rate given by $I = \frac{C\Delta V}{\Delta T}$ or $\Delta T = \frac{C\Delta V}{I}$

If I is a fixed and stable current source and C is a known value then the time to discharge the capacitor to V_{REF} is given by $\Delta T = k(V_{in} - V_{REF})$ when $k = \frac{C}{I}$

The counter will count the clock pulses until the capacitor voltages reach V_{REF} at this point the

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comparator disables the AND gate and signals the microprocessor that the end of conversion (EOC) has occurred.

The key items in this system are the accurate and stable discharge current source and reference voltage. These items use a bandgap voltage reference to as a controlling element. In addition, the clock must be crystal controlled.

This ADC is used to measure battery voltage as well as the voltage across the output storage capacitor. By reading the voltage across the output holding capacitor before and after a pacemaker pulse, a determination of the current supplied to the lead can be made.

The resolution of these voltage readings is 1 mV per bit. Measuring blood temperature can also be determined by applying a fixed current to a thermistor in the heart lead. The voltage across the thermistor is then applied to C and the conversion process is completed as described above. The only difference is that the discharge current is decreased, which allows for readings with more significant digits. Typically the resolution of temperature readings is .004°C per bit.

In the single slope ADC, the microprocessor has complete control of its operation. All of the switches are opened or closed by the micro, and the 15 bit counter can be read at anytime by the microprocessor. The bandgap, current source and reference voltage source can operate down to 1.8 V.

EKG A/D CONVERTER

The second type of A/D converter is used to digitize the EKG waveforms and store the resulting data in the pacer's RAM. This is a high speed analog to pulse width converter. The output of this converter is then gated with a high frequency clock and the output is then totaled in a 7 bit binary counter. A block diagram of this system is shown in Figure 2.

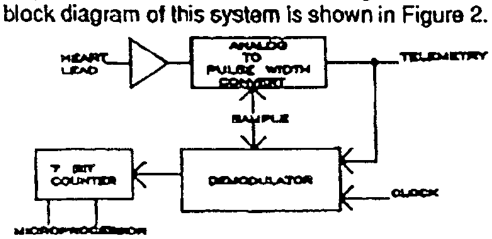

FIGURE 2
EKG A/D

The input signal can be sampled up to 1000 times per second and the sample time set by the microprocessor. The input voltage is amplified and buffered by op amp A1, and the input voltage triggers a monostable whose output pulse width is determined by the amplitude of the input voltage. This output can be transmitted out of the pacemaker for demodulation by the programmer (EKG-TELEMETRY), or it can be demodulated inside the pacer by using a high frequency clock to determine the pulse width of the converted signal. The pulse width is measured using the clock and a 7 bit counter.

The application for this type of A/D are numerous and it lets the microprocessor do digital signal processing of the EKG waveforms. Some applications are as follows:

EKG Pattern Recognition
R-Wave Amplitude Safety Margin
Capture Verification
Storage of Arrhythmia

The limiting factors in this system are the limited RAM available in most pacers and also the high current drain of the clock and continuous operation of the microprocessor. In spite of these limitations, the system can be used to collect information where the A/D operation is triggered by a set of preset conditions. These include a specific R-wave rate, a command from the programmer or a command from microprocessor.

Shown in Figure 3 is a sample EKG waveform, which has been stored in the pacemaker's RAM and uploaded to the external programmer. The data is then formatted and printed out. This waveform shows a ventricular pacer pulse as well as a simulated R-wave. This output is one second long and 1000 samples have been sampled, stored and transmitted to the programmer.

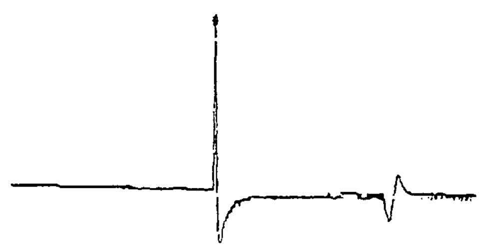

FIGURE 3
DIGITIZED EKG

SUMMARY

In summary, this paper has reviewed a number of analog to digital conversion techniques used in a multi-programmable, rate modulated implantable cardiac pacemaker. These techniques have made the pacemaker a complete physiological monitoring unit. The converting of analog signals into digital signals allows the microprocessor to analyze, store and process a great many important parameters. Future generations of pacemakers will use these techniques to allow the pacer to analyze completely the heart - lead - pacer system.

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